Transportation Research Part D 63 (2018) 421–432

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Through the storm: Transit agency management in response to climate change

Qing Miao[a,*], Mary K. Feeney[b], Fengxiu Zhang[b], Eric W. Welch[b], P.S. Sriraj[c]

[a] Department of Public Policy, Rochester Institute of Technology, 3242 Eastman Hall, 92 Lomb Memorial Drive, Rochester, NY 14623-5604, United States

[b] Center for Science, Technology and Environmental Policy Studies (C-STEPS), Arizona State University, United States

[c] Metropolitan Transportation Support Initiative (METSI), Urban Transportation Center, University of Illinois at Chicago, United States

ARTICLE INFO

Keywords:
Public transit
Extreme weather
Risk perceptions
Climate adaptation
Climate change

ABSTRACT

The increase in extreme weather events due to climate change poses serious challenges to public transit systems. These events disrupt transit operations, impair service quality, increase threats to public safety, and damage infrastructure. Despite the growing risk of extreme weather and climate change, little is known about how public managers recognize, experience and address these risks. Using data from a national study of public transit agencies we investigate the types of extreme weather events transit agencies are experiencing, the associated risks, and how agencies are preparing for them. We find that while extreme events are commonly experienced by transit agencies across states and transit managers perceive increased risks from these events, most agencies rely on the traditional emergency management approach to address extreme weather *ex post* rather than taking a proactive approach to mitigating the adverse weather impact on transit assets and infrastructure ex *ante*. Managers report that a lack of access to financial resources is the greatest challenge for undertaking adaptation and preparation. We conclude with a discussion of what these findings mean for understanding organizational adaptation behavior as well as climate adaptation policy making.

1. Introduction

Extreme weather events such as floods, heat waves, hurricanes and severe storms pose serious challenges to public transit systems. Not only do they disrupt transit operations, impair service quality, and cause additional safety threats, but they also damage infrastructure and impose stress on the state of good repair. As demonstrated by Hurricane Sandy and other recent weather-related disasters, the weather impacts on transit can have significant ramifications for regional mobility and functioning of economic systems, given the public's increased reliance on transit systems for access to jobs and other services. How to effectively manage the risks of extreme weather is a question that constantly concerns transit managers. This issue has become increasingly urgent as climate change is resulting in more frequent and intense extreme weather events (IPCC, 2012; NOAA, 2017). While many transit agencies have experience and expertise coping with weather disruptions, they are confronted with the new challenge of identifying and developing appropriate long-term adaptation strategies to address greater risk and uncertainty associated with climate change (Thomson, 2017).

In this paper, we investigate how public transit managers perceive extreme weather risk and how their agencies respond to and prepare for these growing challenges. Using data from a national survey of 273 public transit organizations, we show how U.S. transit

* Corresponding author.
E-mail address: qxmgla@rit.edu (Q. Miao).

https://doi.org/10.1016/j.trd.2018.06.005

Available online 15 June 2018
1361-9209/ © 2018 Elsevier Ltd. All rights reserved.

agencies are responding to extreme weather associated with climate change and document the potential barriers they face in the adaptation process. We draw from perspectives of managers in planning, operations, maintenance, and engineering to assess recent experiences with extreme weather events, the impacts of extreme weather on agency operations, strategies and approaches employed to manage and adapt to extreme weather risks, and managerial perceptions of agency capacity. While similar survey studies have been conducted in other sectors such as coastal management and public health (e.g. Tribbia and Moser, 2008; Bedsworth, 2008), our research presents one of the first few attempts to examine the current status of adaptation responses in the broader U.S. public transportation sector. Given the wide breadth of adaptation options, we are particularly interested in understanding whether agencies are primarily engaged in reactive emergency responses or proactive adaptation and planning activities, and how they interact and coordinate with other organizations in managing local and regional extreme weather events.

The paper is organized as follows. In the next section, we review the relevant literature. We then describe our research design and methodology in Section 3 and present the main results in Section 4. Section 5 discusses the implications of the results and Section 6 draws conclusions.

2. Relevant literature

Transit systems are highly sensitive to weather interruptions because of the nature of the service they provide and because many of their assets and infrastructure are exposed to the environment. There is a growing body of research examining the impact of weather and climate change on transportation (Suarez et al., 2005; Chapman, 2007; Koetse and Rietveld, 2009; Jochem et al., 2016; Pregnolato et al., 2017; Xia et al., 2013; Stamos et al., 2015). There is also increased research attention to understanding the relationships between weather and public transit. For example, several recent studies have investigated how adverse weather conditions (e.g. extreme high or low temperatures and excessive precipitation) affect urban transit ridership, finding an overall negative impact (e.g. Guo et al., 2007; Stover and McCormack, 2012; Cravo and Cohen, 2009; Changnon, 1996; Singhal et al., 2014; Arana et al., 2014; Kalstein et al., 2009). Such findings imply that unfavorable weather conditions result in a direct revenue loss for transit service providers.

Extreme weather affects the availability and the quality of transit service as well as the physical transit infrastructure (Chung, 2013; Flegenheimer, 2013; Hodges, 2011). Singhal et al. (2014) show that adverse weather conditions disrupt routine transit operation by increasing access time, prolonging trip duration, reducing service frequency, and causing vehicle rerouting. Climate change is expected to intensify the weather risks to the transit systems. In a recent report published by the Federal Transit Administration (FTA), Hodges (2011) identifies four primary climate stressors facing public transit including intense precipitation, heat waves, rising sea levels, and hurricanes. Specifically, intense precipitation, hurricanes, and sea level rise can flood tracks, bus ways, tunnels, and facilities, while extreme heat waves can cause track buckling and lead to delays or derailing. Overall, the revenue loss due to physical infrastructure damage and reduced transit usage may impair the financial conditions of most local transit agencies and also result in additional public spending at different levels of government. Furthermore, considering the populations who most likely rely on public transportation, extreme weather events give rise to social equity concerns due to their disproportionate impacts on the elderly, people with disabilities, and low-income individuals.

While there is a recognized need for organizations to adapt to the impacts of extreme weather and climate change (Linnenluecke et al., 2012; Winn et al., 2011; Nelson et al., 2007; Smithers and Smit, 1997), little research has examined how transit agencies have dealt with weather-related disruptions and in particular, the dynamics of their organizational decisions and responses related to extreme weather. It should be noted that extreme weather is not necessarily a new phenomenon. Many transit agencies have long experience coping with extreme weather events, with a traditional focus on an emergency management approach (i.e. treating these events as emergencies and developing emergency response plans). The existing literature on adaptation and resilience has represented a paradigm shift that places more emphases on developing anticipatory, planned strategies and building capacity to manage external changes including increased climate variability and disastrous weather conditions (Folke, 2006; Hegerl et al., 2007; Adger et al., 2011; Berkhout, 2012; Zhang et al., 2018).

With respect to the public transit sector, recent studies have proposed a variety of adaptation options based on their identification of climate and weather-related risk specifically concerning transit. For example, the 2008 report of the Transportation Research Broad (TRB) suggested transportation professionals take a comprehensive and risk-based approach by integrating climate factors to the planning, design, construction, operation, and maintenance of transportation systems (DOT, 2014). Hodges (2011) has classified transit adaptation strategies into four major categories, which include (1) maintain and manage: absorb the costs of increased maintenance and repairs while improving real-time responses to severe events; (2) strengthen and protect: develop new assets and infrastructure to withstand future events; (3) enhance redundancy: identify alternative services and routes to ensure service continuity during extreme events, anticipating and preparing for the loss of a link in the entire transit network; and (4) retreat: abandon transportation infrastructure located in indefensible or extremely vulnerable areas and relocate to areas less susceptible to extreme weather events.

Based on Hodges' (2011) framework, we examine the current status of adaptation across U.S. public transit agencies to provide the first comprehensive national survey of transit risks and responses related to extreme weather and climate change. Our research draws upon the study conducted by Koch and MacArthur (2013), which used an online survey and content analysis to empirically examine whether and how public transit agencies adapt to the impacts of climate change. They found that only 17 agencies were

explicitly involved in climate adaptation activities, mostly through the FTA-funded pilot projects.[1] Koch and MacArthur (2013) suggested that the common barriers to transit system adaptation include lack of funding, lack of access to information and tools, and lack of organizational priorities. Our study extends their work by including a larger and nationally representative sample of transit agencies and asking more explicitly about how these agencies deal with extreme weather to assess their preparedness for climate change. Moreover, our study distinguishes between reactive emergency responses and proactive adaptation and planning, aiming to provide a more comprehensive picture of the current state of practices within transit agencies in managing weather risks.

3. Data and method

We developed a sample frame that is representative of the national population of relevant transit agencies. From the National Transit Database (NTD), the research team selected all major fixed-route transit agencies operating bus or rail transit services in metropolitan areas across the United States with annual fare revenue of at least one million dollars in 2013. As a result, smaller agencies that have few vehicles in operation and generally do not regularly report their operating data to NTD are excluded from the study. The final sample frame included 273 transit agencies.

We recognize that the perspectives and experiences of transit agencies are not monolithic and that responses would likely vary depending upon the professional background and position of the survey participant and the transit conditions and climate in each city. Therefore, we identified the lead managers of the following five major departments in each agency: operations, maintenance, service planning, strategic planning, and engineering. We collected individual names and contact information from publicly available online listings, and by making telephone calls and the Freedom of Information Act requests, which resulted in a final sample frame of 892 respondents.

As part of the survey development process, we conducted formal interviews with individuals in planning, engineering, operations, communications, and finance departments from a purposive sample of four transit agencies in different parts of the United States. The interviews served to increase the research team's knowledge about how extreme weather affects transit agencies and to further identify and articulate many of the questions in the survey instrument, especially those which might be subject to localized variation or particularities.

We undertook the survey design as an iterative process, guided by both the study aims, the interviews, as well as the literature related to extreme weather, public transit, risk management and adaptation to climate change. The final survey instrument was coded as an online web-based survey in Sawtooth Software® and pretested on a random sample of 20 individuals. After dropping the unreachable, retired and ineligible individuals, the online survey was administered to an adjusted sample of 862 public officials from 273 transit agencies from April 28, 2016 through June 11, 2016 with repeated follow up contacts encouraging participation. We closed the survey with 306 complete responses, yielding a response rate of 35.5%. Post-analysis showed no significant differences between the responding and non-responding agencies by size ($p = 0.481$), or region ($p = 0.543$).

Of the 273 transit agencies surveyed, we received at least one response from 199 (73%) agencies and 39 of the 50 states. Of the 11 states not represented, seven do not have transit agencies of our interest (HI, ID, MT, ND, NH, SD, and WY). Fig. 1 shows the geographic distribution of the transit agencies that participated in our survey based on the nine U.S. Census regional divisions.[2] A majority of the responding agencies are independent transit authorities (64%) with the remainder mostly operated by city governments (33%). Nearly 43% of the responding agencies contract with another organization to provide either part or all of their transit services. The average total revenue of responding agencies as reported by NTD is $51.5 million; the median revenue is $4 million. The majority of the 199 responding agencies operate only bus services (147, 74%). While most of the remaining agencies (42, 21%) operate a combination of bus and rail or bus and water, only 10 agencies (5%) operate exclusively rail (heavy or light) transit services. We provide more details about the participating agencies and information about the demographic and professional background of individual respondents in Appendix A.

The survey opened with the following definition of extreme weather events: "*Extreme weather events include unusually severe storms, floods, heat waves or other weather incidents that lie outside of historic norms or experience*." Respondents were asked a series of questions about their experiences with extreme weather events (including the types of events and their responses) over the previous two-year time frame and planning and operations for future events. The two-year time frame was tested in our pre-test and determined to be appropriate for being long enough to capture a variety of events, while minimizing respondent recall problems.

4. Results

This study is concerned with answering four research questions, which aim to provide a baseline for understanding U.S. public transit agency preparedness for dealing with extreme weather and climate change. First, what are the types of extreme weather events that transit agencies are experiencing? Second, what are the impacts of those events on the transit systems? Third, what are transit managers' perceptions of the risks associated with extreme weather events? Fourth, how are agencies preparing to respond to these risks? Below we present our initial findings on these questions.

[1] FTA launched the Climate Change Adaptation Initiative in 2011 and committed $1 million in research funding to pilot projects to advance the state of practice for adapting transit system to the impacts of climatic variability. The program involved nine transit agencies in seven metropolitan locations, including Chicago Transit Authority, San Francisco Bay Area Rapid Transit, Gulf Coast, Los Angeles County Metropolitan Authority, Metropolitan Atlanta Rapid Transit Authority, Southeastern Pennsylvania Transportation Authority and Central Puget Sound Regional Transit Authority. The project outputs primarily consist of vulnerability and risk assessment and climate risk reduction strategies, which were published in August 2014.

[2] In the analysis, we examine the impacts of extreme weather that transit agencies have experienced by geographic regions. We use the regional division criteria from the U.S. Census. (https://www.census.gov/geo/reference/gtc/gtc_census_divreg.html).

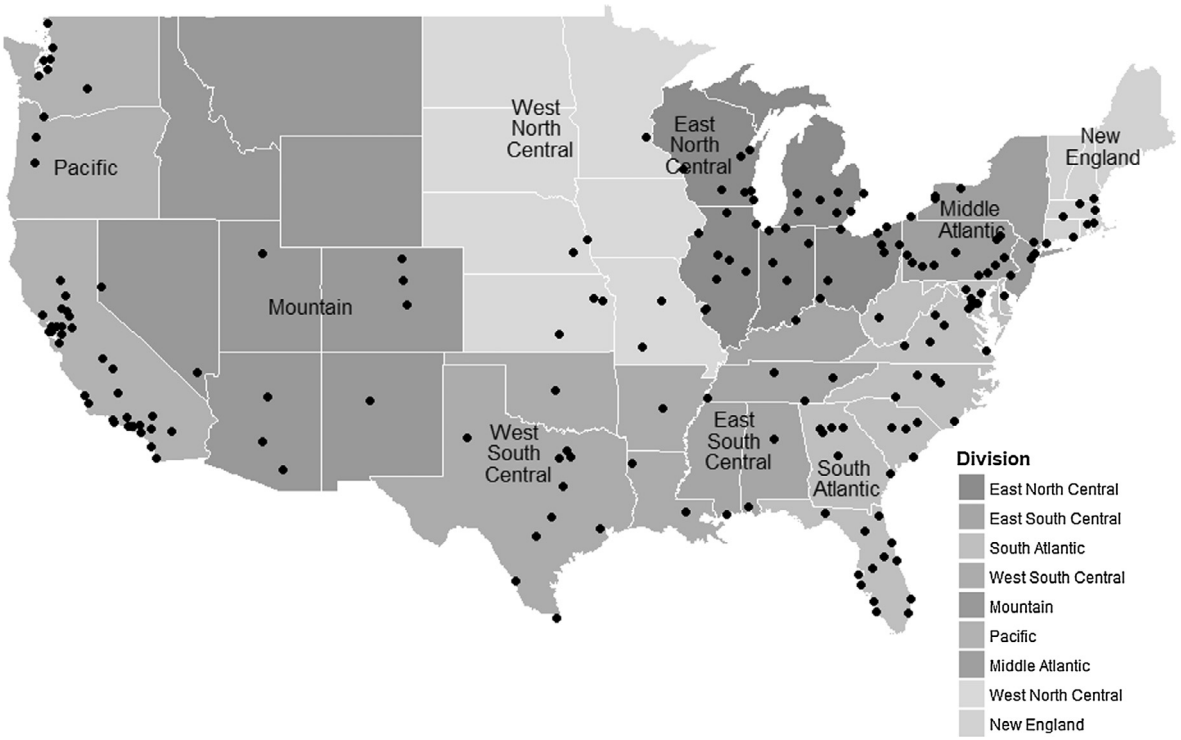

Fig. 1. Geographic distribution of responding agencies by state and region. Note: Alaska and Hawaii are not represented in the final data set.

4.1. Extreme weather types

First, we identify the types of extreme weather events managers in transit agencies across the US report they are experiencing. Our results indicate that severe rainstorms/thunderstorms are the most frequent type of extreme weather event experienced by U.S. transit agencies, followed by extreme cold, extreme high winds, and extreme heat waves.[3] For example, 105 managers (35%) reported two to three severe rainstorms or thunderstorms over the past two years and 122 (41%) reported more than three times. More than half of the respondents (177, 58%) reported at least two extreme cold weather events. In contrast, hurricanes, tropical storms, and storm/tidal surges were experienced less frequently across the nation due to their geographical specificity. On average, transit agency managers experienced two to three extreme events over the past two years. Their experiences with extreme weather vary substantially depending on geographic locations. Specifically, managers in New England report significantly more extreme snowstorms than those in other regions ($p < 0.000$), while those in the South Atlantic region report significantly more hurricanes and tropical storms than those in other regions ($p < 0.000$).

While there are no significant differences by respondent position within the transit agency, managers working at the safety department or emergency management function, on average, report higher frequencies of extreme weather events ($p < 0.020$) than managers in other functions (e.g. CEOs/general managers, engineers, maintenance, operation, planning).

4.2. Impacts of extreme weather events

Our second research question seeks to identify the impacts of extreme weather events. We asked all respondents who had experienced at least one extreme event to assess the severity of the event(s) in terms of the adverse impact on their local areas. Table 1 presents responses to a question about the severity of extreme events. About 35% of the respondents reported that extreme snowstorms had caused major or catastrophic impact, while 15% of respondents reported major or catastrophic impacts as a result of hurricanes or tropical storms. Events that occur more frequently – severe rainstorms/thunderstorms, extreme cold temperatures, and extreme high winds – are ranked slightly lower in the resulting severity of their impacts.

We asked respondents to identify one single extreme weather event that had the most adverse impact on their agencies during the past two years. More than half of the respondents identified a snowstorm (41%) or floods/heavy rainfall (14%). The snowstorm events are significantly more likely to affect agencies in the East North Central ($p < 0.000$), Middle Atlantic ($p < 0.000$) and New England ($p < 0.048$) regions. Floods or heavy precipitation are more likely to be a severe threat for agencies in the West South

[3] The original survey question asked: "During the last two years, about how many times have the following extreme weather events occurred in your transit service area?" The respondents can indicate the frequency by choosing from "never, once, two or three times, more than three times."

Table 1
Severity of extreme weather events that occurred in the past two years.

Extreme weather events	No impact	Minor impact	Moderate impact	Major impact	Catastrophic impact	N
Severe rainstorms/thunderstorms	13%	51%	30%	6%	0%	267
Extreme cold temperatures	16%	46%	29%	9%	0%	210
Extreme high winds	18%	49%	25%	8%	0%	232
Extreme heat waves	18%	52%	25%	5%	0%	219
Extreme snowstorms	3%	20%	42%	33%	2%	171
Floods	14%	46%	30%	9%	1%	153
Tornadoes	24%	50%	22%	3%	1%	100
Wildfires	31%	45%	20%	4%	0%	65
Hurricanes/tropical storms	21%	41%	23%	13%	2%	61
Tides/storm surges	20%	37%	31%	9%	3%	35

Central ($p < 0.012$). Importantly, only 23 percent of the respondents indicated that their region had not experienced an extreme weather event in the past two years. Transit agencies located in the Pacific region are significantly more likely to report no events compared to others ($p < 0.004$).

Respondents reported important outcomes of the extreme weather event they had selected (Table 2). The most common consequences were significant delays in transit service (72%), followed by temporary shutdowns (56%) and damage to vehicles or equipment (31%). One in five respondents indicated that extreme weather resulted in complete or partial failure of transit services or systems and damage to infrastructure or facilities.

As illustrated in Table 3, the resulting impacts of a single extreme weather event vary significantly by the transit mode of the agency. Respondents working in agencies that provide rail-based transit services (including both light rail and heavy rail) report damage to infrastructure or facilities ($p < 0.000$) and complete failure of portions of transit service systems ($p < 0.059$) due to extreme weather more frequently than those working in agencies that deliver bus transit only or bus and water transit services exclusively. At the same time, transit agencies that operate bus only, as compared to other transit modes, are significantly less likely to report damage to infrastructure or facilities ($p < 0.000$) or complete failure of portions of the transit services or systems ($p < 0.071$).

In terms of geographic variation, we find that significant delays due to extreme weather are more likely to be reported by transit managers located in the East North Central ($p < 0.042$), Middle Atlantic ($p < 0.098$), Mountain ($p < 0.060$), and New England ($p < 0.058$) regions. Temporary shutdowns in transit service are more likely to happen to agencies in the Middle Atlantic ($p < 0.064$), New England ($p < 0.006$), South Atlantic ($p < 0.000$), and West South Central regions ($p < 0.033$).

Overall, we do not find strong evidence on the variation in the reporting of extreme weather disruption of transit systems by respondents' managerial positions. One exception is that the general managers and directors (including CEOs) of a transit agency are significantly more likely to report temporary shutdowns due to extreme weather compared to others ($p < 0.006$). In addition, engineers are more likely to report damage to vehicles and equipment as a result of extreme weather ($p < 0.079$).

4.3. Perceived risks of extreme weather

Our third research question asks how transit managers perceive the risks associated with extreme weather events. First, we find that extreme weather is a growing concern for transit managers across the country. Over 40% of all respondents "agree" or "strongly agree" that extreme weather is becoming more frequent. Half of the respondents "agree" or "strongly agree" that they are increasingly concerned about the impact of extreme weather on transit infrastructure (48%) and operations (50%). A stark minority of respondents (3%) agree or strongly agree that extreme weather events are becoming less severe.

In terms of geographic variation, the results presented in Table 4 indicate that transit managers located in the South Atlantic region report significantly higher levels of concerns with the impact of extreme weather on their transit infrastructure ($p < 0.018$), whereas respondents in the Pacific region are less concerned with the same problem ($p < 0.007$). Respondents in the Middle Atlantic ($p < 0.090$), New England ($p < 0.075$), and South Atlantic ($p < 0.005$) regions as compared to other regions report significantly

Table 2
Impact on the transit system as a result of the most adverse weather event.

Weather Impacts	N	% Yes
Significant delays in transit services	241	72%
Temporary shutdown in transit services	241	56%
Damage to vehicles or equipment	241	31%
Complete failure of portions of transit services or systems	241	21%
Damage to infrastructure or facilities	241	22%
Passenger or operator injuries	241	11%
Passenger or operator loss of life	241	0%
Other injuries or loss of life (e.g. bystanders)	241	2%

Table 3
Extreme weather impacts on the transit systems by transit mode.

Weather Impacts on Transit Systems	Contrast between rail (light or heavy) and non-rail (bus only/bus & water) transit modes	Std. Err	t	p > |t|
Significant delays in transit services	0.05	0.06	0.75	0.451
Temporary shutdown in transit services	0.11	0.07	1.54	0.124
Damage to vehicles or equipment	0.03	0.07	0.45	0.650
Complete failure of portions of transit services or systems	0.11	0.06	1.9	0.059
Damage to infrastructure or facilities	0.25	0.06	4.27	0.000
Passenger or operator injuries	−0.03	0.05	−0.64	0.525
Passenger or operator loss of life	−0.01	0.01	−0.61	0.540
Other injuries or loss of life (e.g. bystanders)	−0.02	0.02	−1.24	0.217
Weather Impacts on Transit Systems	Contrast between bus only and other transit modes	Std. Err	t	p > |t|
Significant delays in transit services	−0.03	0.06	−0.52	0.603
Temporary shutdown in transit services	−0.10	0.07	−1.37	0.171
Damage to vehicles or equipment	−0.04	0.07	−0.67	0.506
Complete failure of portions of transit services or systems	−0.11	0.06	−1.81	0.071
Damage to infrastructure or facilities	−0.26	0.06	−4.55	0.000
Passenger or operator injuries	0.03	0.05	0.68	0.494
Passenger or operator loss of life	0.01	0.01	0.62	0.536
Other injuries or loss of life (e.g. bystanders)	0.02	0.02	1.25	0.212

Table 4
Geographic variation in risk perception.

Regions	Contrast	Std. Err	t	p > |t|
Panel A. Perceived extreme weather impact on transit infrastructure				
East North Central vs. all others	0.0675	0.167575	0.4	0.688
East South Central vs. all others	−0.5308	0.3080	−1.72	0.086
Middle Atlantic vs. all others	0.3242	0.2157	1.5	0.134
Mountain vs. all others	−0.2989	0.2411	−1.24	0.216
New England vs. all others	0.5159	0.3682	1.4	0.162
Pacific vs. all others	−0.3876	0.1429	−2.71	0.007
South Atlantic vs. all others	0.3617	0.1522	2.38	0.018
West North Central vs. all others	0.1425	0.2724	0.52	0.601
West South Central vs. all others	−0.0648	0.2368	−0.27	0.785
Panel B. Perceived extreme weather impact on transit operation				
East North Central vs. all others	0.0885	0.1551207	0.57	0.569
East South Central vs. all others	−0.3929	0.2855	−1.38	0.170
Middle Atlantic vs. all others	0.3397	0.1995	1.7	0.090
Mountain vs. all others	−0.3226	0.2229	−1.45	0.149
New England vs. all others	0.6081	0.3400	1.79	0.075
Pacific vs. all others	−0.4515	0.1321	−3.42	0.001
South Atlantic vs. all others	0.3942	0.1405	2.81	0.005
West North Central vs. all others	0.1819	0.2520	0.72	0.471
West South Central vs. all others	−0.1755	0.2235	−0.79	0.433

higher concerns with extreme weather effects on transit operations. With regard to the respondents' position, we find that managers who are in charge of safety and emergency management are more likely to report increased concerns with extreme weather effects on infrastructure ($p < 0.015$).

Since different types of extreme weather events could pose varying levels of risk to transit agencies, we also asked transit managers about their expectations of future risks by event type. Specifically, we asked respondents to rate the severity that different types of extreme weather events would pose for their agencies in the next ten years (rating on the following scale: 1 = very low risk; 2 = low risk; 3 = slight risk; 4 = high risk; 5 = very high risk). Transit managers perceive rainstorms/thunderstorms to pose the highest risk (mean = 3.15, std. dev. = 1.05, n = 302), followed by extreme high winds (mean = 2.88, std. dev. = 1.15, n = 303), extreme heat waves (mean = 2.82, std. dev. = 1.12, n = 301), extreme snowstorms (mean = 2.73, std. dev. = 1.44, n = 303), extreme cold temperatures (mean = 2.57, std. dev. = 1.23, n = 303), and floods (mean = 2.50, std. dev. = 1.09, n = 304).

We further examine how the general perceptions of extreme weather risk to transit infrastructure and operations are associated with respondents' perceptions of specific types of extreme weather. Specifically, we regressed the two variables on perceived extreme weather impact on transit operation and infrastructure on the aforementioned variables measuring perceived future risk of each of

Table 5
Correlation between general perceived risk on transit systems and hazard-specific risk perceptions.

Dependent variables	EW impact on infrastructure		EW impact on operation	
Model	OLS	Ordered Logit	OLS	Ordered Logit
Extreme cold temperatures	0.164**	0.239*	0.101	0.178
	(0.0789)	(0.141)	(0.0702)	(0.142)
Extreme heat waves	−0.0497	−0.0479	−0.0227	−0.00498
	(0.0636)	(0.114)	(0.0566)	(0.117)
Wildfires	0.0517	0.0811	−0.0232	−0.0764
	(0.0648)	(0.119)	(0.0577)	(0.120)
Floods	0.109	0.176	0.103	0.183
	(0.0738)	(0.137)	(0.0658)	(0.136)
Hurricanes/tropical storms	0.138**	0.264**	0.203***	0.426***
	(0.0673)	(0.125)	(0.0599)	(0.130)
Severe rainstorms/thunderstorms	−0.0279	−0.0938	0.0518	0.118
	(0.0839)	(0.158)	(0.0747)	(0.156)
Tides/storm surges	0.0593	0.170	−0.0287	0.00995
	(0.0827)	(0.155)	(0.0737)	(0.159)
Extreme high winds	0.118	0.218	0.0962	0.194
	(0.0755)	(0.138)	(0.0671)	(0.141)
Tornadoes	0.0190	0.0310	0.00647	−0.0136
	(0.0623)	(0.111)	(0.0554)	(0.117)
Extreme snow storms	0.0675	0.184	0.113*	0.261**
	(0.0680)	(0.123)	(0.0605)	(0.122)
Observations	290	290	289	289

Notes: all the independent variables are drawn on our survey items asking respondents to rate the level of risk, in the next ten years for each type of the extreme weather events in their region on a five-point scale. Larger values indicate a higher level of perceived risk.

Table 6
Pearson's correlation coefficients between recent experiences and risk perception by type of extreme weather.

		Frequency of extreme weather events in the past two years									
		1	2	3	4	5	6	7	8	9	10
Future risk perception	1. Severe rainstorms /thunderstorms	0.738***									
	2. Extreme high winds		0.529***								
	3. Extreme heat waves			0.621***							
	4. Extreme snow storms				0.484***						
	5. Extreme cold temperatures					0.639***					
	6. Floods						0.497***				
	7. Tornadoes							0.704***			
	8. Wildfires								0.552***		
	9. Hurricanes /tropical storms									0.593***	
	10. Tides /storm surges										0.800***

Note: *** Significance at the 1 percent level.

the ten types of extreme weather.[4] Table 5 reports our estimation results from the ordinary least squares (OLS) and ordered logit models, respectively. We show that, among all types of extreme weather, the perceived future risk of hurricanes or tropical storms significantly correlates with perceived extreme weather impact on both transit infrastructure and operation. In addition, perceptions of risk related to extreme cold temperatures are significantly related to perceived weather risks to infrastructure, whereas the risk of snowstorms is related to managerial perceptions about risk to transit operations.

The risk perception literature generally suggests that perceptions of environmental hazards are influenced by previous hazard experiences (Eiser et al., 2012; Grothmann and Patt, 2005; Berrang-Ford et al., 2011). Drawing from their experiences dealing with extreme weather, we took a further step by examining the link between managers' recent experiences with extreme weather and their perceptions of the future risk for each type of event. Table 6 reports the Pearson's correlation coefficients, showing the high correlation between the frequency of extreme weather event and the perception of future risk. Given the high consistency between past experiences and perceived hazard-specific risk for future, the latter one is also highly geographically dependent. For example, agencies located in the New England ($p < 0.000$), East North Central ($p < 0.000$), and West North Central ($p < 0.002$) regions perceive significantly higher risk of snowstorms in the future.

[4] The dependent variables are based on two survey items which asked respondents to indicate their level of agreement with two separate statements (from strongly disagree to strongly agree): (1) my agency is increasingly concerned about the impact of extreme weather events on our transit infrastructure; and (2) my agency is increasingly concerned about the impact of extreme weather on our transit operations. Larger values indicate higher levels of concerns. Because the dependent variables are both ordinal variables with a 0–5 scale, we also use the ordered logit model in addition to the OLS model.

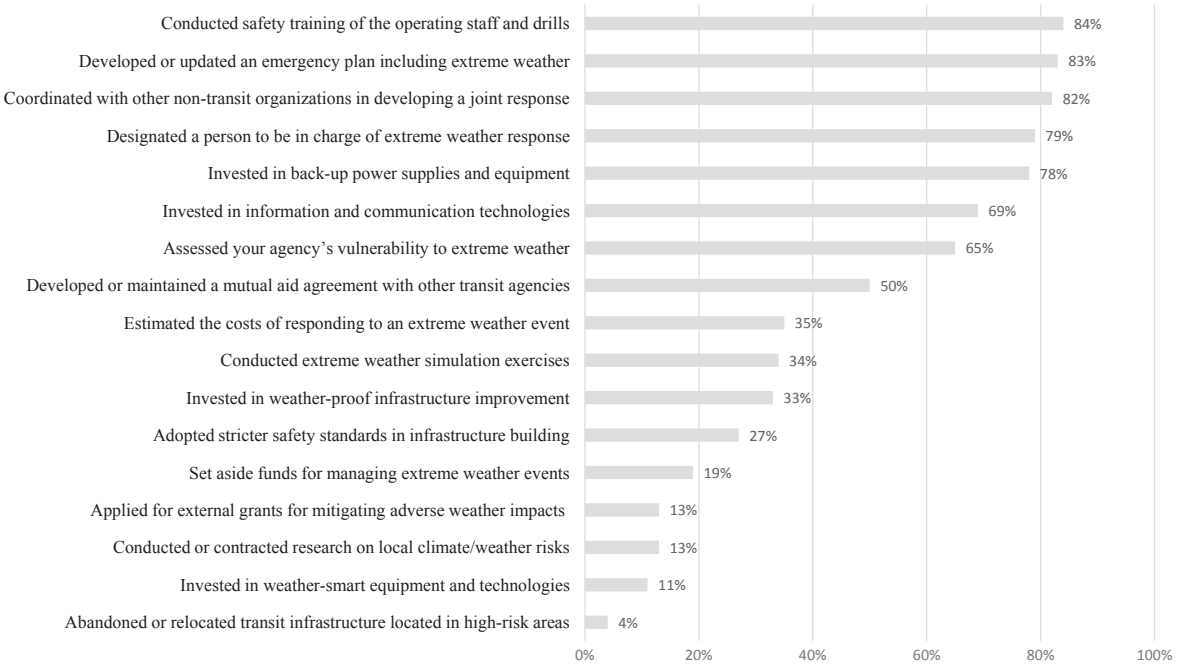
Conducted safety training of the operating staff and drills 84%
Developed or updated an emergency plan including extreme weather 83%
Coordinated with other non-transit organizations in developing a joint response 82%
Designated a person to be in charge of extreme weather response 79%
Invested in back-up power supplies and equipment 78%
Invested in information and communication technologies 69%
Assessed your agency's vulnerability to extreme weather 65%
Developed or maintained a mutual aid agreement with other transit agencies 50%
Estimated the costs of responding to an extreme weather event 35%
Conducted extreme weather simulation exercises 34%
Invested in weather-proof infrastructure improvement 33%
Adopted stricter safety standards in infrastructure building 27%
Set aside funds for managing extreme weather events 19%
Applied for external grants for mitigating adverse weather impacts 13%
Conducted or contracted research on local climate/weather risks 13%
Invested in weather-smart equipment and technologies 11%
Abandoned or relocated transit infrastructure located in high-risk areas 4%
0%
20%
40%
60%
80%
100%

Fig. 2. Strategies used by transit agencies to deal with extreme weather and climate risks (% Yes).

4.4. Preparing for extreme weather events

Our fourth research question seeks to understand how US transit agencies respond to and prepare for weather-related risks. In particular, are transit agencies reactively or proactively adapting to extreme weather? Because we are interested in how transit agencies are preparing for these challenges, we collapse the individual responses to the agency level (N = 199). We present our findings related to agency responses to extreme weather, including long-term plans, investments in technology and facilities to prepare for extreme weather, and the collaborative efforts to enable public agencies to better respond to extreme weather events.

Our results indicate that agency responses to prepare for weather events include some proactive planning, but overall are reactive and related to the traditional emergency management approaches (preparation on undertaking emergency responses on the operational level). As shown in Fig. 2, within the past two years, the majority of agencies have developed or updated an emergency plan including extreme weather (83%), conducted safety training of the operating staff and drills (84%), and designated a person to be in charge of extreme weather response (79%). Many agencies also report working with other stakeholders to prepare. For example, 82% report that they have coordinated with other organizations (other than transit agencies) in developing a joint response while 50% report they have developed or maintained a mutual aid agreement (or other collaborative relationships) with other transit agencies. One-third of the responding agencies have conducted simulation exercises to prepare for extreme weather events.

Transit agencies take a number of steps to plan for and mitigate the effects of extreme weather. The most common strategies reported include investing in back-up power supplies/equipment (78%) and information and communication technologies (69%). These risk-mitigating strategies are relevant to addressing a broad range of emergency situations, not just extreme weather. Two-thirds of all agencies (65%) in this study have assessed their vulnerability to extreme weather, but only a third of agencies reported that they have assessed costs related to extreme weather response (35%). Even fewer agencies have adopted proactive climate adaptation strategies such as asset protection (33%), set aside funds for managing extreme weather events (20%), and abandoned or relocated infrastructure in areas where extreme weather risks are high (5%).

We performed additional tests to look into whether and how the adoption of different adaptation strategies may vary by transit mode or regions (Table 7). We find that while transit agencies operating different modes do not exhibit significant differences in terms of the emergency response approach (e.g. making emergency plans, safety training or drills), transit agencies that operate rail services are significantly more likely to adopt adaptation-related measures (e.g. vulnerability assessment, adaptation cost assessment, investment in weather-resilient equipment and technologies, information and community technologies, back-up power supplies, weather-proof infrastructure improvement) than agencies that operate non-rail services (bus only or bus and water). Meanwhile, we find that geographic regions have little correlation with the type of adaptation strategies taken by transit agencies.

During extreme weather events, transit agencies are rarely the sole responder. Transit agencies typically collaborate and coordinate with other external stakeholders and organizations as a joint response to extreme events. Managing extreme weather also requires considerable internal coordination among different functions within the same transit systems. We find that transit agencies coordinate with a variety of stakeholders using specially designed protocols in the event of extreme weather. The most common stakeholders that transit agencies focus their coordinated response effort on are transit riders. Nearly all responding organizations

Table 7
Transit risk management measures by transit mode.

Agencies' adoption of risk management measures	Contrast between rail and non-rail agencies	Std. Err	t	p > |t|
1. Conduct emergency planning	0.018	0.0502	0.37	0.715
2. Conduct safety training and drills	0.045	0.0512	0.89	0.376
3. Assess vulnerability to extreme weather	0.242	0.069	3.51	0.001
4. Assess costs of responses to extreme weather	0.316	0.074	4.24	0.000
4. Invest in weather-smart equipment and technologies	0.124	0.0526	2.35	0.020
5. Invest in information and communication technologies	0.111	0.0651	1.71	0.089
6. Invest in back-up supplies and equipment	0.163	0.0573	2.84	0.005
7. Invest in weather-proof infrastructure improvement or retrofitting projects	0.261	0.069	3.75	0.000
8. Conduct research on extreme weather	0.184	0.056	3.28	0.001

(91%) report coordinating responses with riders including using special protocols to communicate with riders during an extreme weather event. In addition, coordination activities are prevalent with emergency management agencies, local government departments, and other local transit agencies based on specially-designed protocols. Only about 16% of the agencies indicated that they do not have specifically designed protocols, although that does not necessarily indicate a lack of coordination with other stakeholders or organizations.

5. Discussion

Climate change can have a profound effect on every mode of transportation across the United States (TRB, 2008). As a result of climate change, more extreme weather events are expected to occur, which lie beyond an organization's coping range and pose new and unexpected challenges. While numerous studies have assessed the impact of extreme weather and climate change on transportation, relatively little attention has been paid to how transit agencies perceive the climate risk and the need for long-term adaptation. Even less is known about their current approaches to managing extreme weather risks and investments in adaptation strategies.

With respect to the perception of weather risks, about half of the managers in our survey report that extreme weather events are occurring more frequently and becoming more severe in coming years. Managers are increasingly concerned with the impacts of extreme weather on transit systems. Our analysis suggests that the perception of future weather risks is influenced by recent experiences with extreme weather events, which varies by geographic region. In particular, weather hazards such as hurricanes, tropical storms, and snowstorms have caused particularly disruptive effects on transit systems by causing delays, temporary shutdowns, and damage to the equipment. Accordingly, transit managers located in regions that are highly exposed to these risks (e.g. South Atlantic, New England) perceive significantly higher risks of extreme weather events for their agencies.

In terms of organizational responses, we find that the majority of transit agencies in our study have been undertaking measures to address their local risks associated with extreme weather. They have predominantly relied on the traditional emergency management approach to address extreme weather (e.g. hired professionals in charge of emergency management; developed emergency plans; conducted safety training). Their preparation for extreme weather has mainly focused on what to do after an emergency, rather than how to reduce their vulnerability to weather shocks *ex ante*.

We find that transit agencies are more likely to adopt generic risk-mitigating strategies (e.g. information technology, investing in back-up power supplies) to maximize benefits under various emergency situations. We also find that rail-based transit agencies take more proactive measures to adapt to extreme weather risks, likely because they have more fixed and directly exposed infrastructure. Rail-based transit agencies report more frequent interruptions and damage caused by extreme weather, which might lead to more adaptations. Overall, many agencies are still in the stage of identifying and assessing their vulnerabilities to weather risks, and few have adopted climate-specific adaptation strategies such as asset protection and infrastructure retrofitting. These results advance the findings of Koch and MacArthur (2013), suggesting there is a non-negligible gap between the awareness of weather risks and actual risk-mitigating actions.

Many factors may simultaneously affect organizational adaptation decisions, including access to financial resources. Because planning and preparing for extreme weather events is costly, failure to adopt these strategies may be partly attributed to the lack of financial resources. In the survey, we asked the respondents to assess factors that may limit their agency's ability to prepare for extreme weather. More than 25% of them considered the lack of financial resources to be a very significant or extremely significant barrier, and one third considered it to be moderately significant. Respondents also identified a lack of internal coordination and awareness of extreme weather risks as two major barriers to agency adaptation to climate risks. This finding is consistent with the general observation in the adaptation literature that organizational adaptation is not solely driven by risk perception but also influenced by their adaptive capacity (Berkhout, 2012). This suggests that government should provide more financial support or incentives for these agencies to invest in climate-resilient infrastructure and technologies. Post-disaster aid can provide an opportunity to upgrade transit facilities, which could potentially lead to improved resilience. For example, in 2014, the U.S. Department of Transportation provided $886 million to New York Metropolitan Transportation Authority to help it restore and replace the facilities damaged by Hurricane Sandy (Friedman, 2014).

Transit agencies may continue to invest in emergency management strategies because of their higher level of familiarity with this

area relative to adaptation. When asked to assess their agency's capacity for managing extreme events, most managers indicated a moderate-to-high level of confidence in coping with extreme weather events. Many report that their agencies possess adequate weather information, internal expertise and staff, and adequate emergency plans that enable their agencies to effectively respond to these events in the future. This suggests that the confidence respondents have in their agencies' abilities to address extreme weather is generally based on the application of traditional emergency response methods rather than a proactive planning approach.

In sum, our research findings are of value to the ongoing discussion about increasing urban resilience to extreme weather and climate change, particularly when recent catastrophes have drawn public attention to natural disasters. Nonetheless, it is important to acknowledge that we focus on the descriptive statistics of the survey response data to make inferences about the perception of weather risks among transit managers and the extent to which they have considered and incorporated these risks in their organizations' planning, operation, and maintenance activities. Additional analyses could be performed to investigate the relationship between perceived risks and the scope of agency-level adaptation efforts and to identify the factors that may explain organizational decision making related to extreme weather and climatic risks. Furthermore, while our research provides preliminary evidence that these agencies' risk perception is in line with their recent experiences with extreme weather, it is questionable whether agencies or transit managers are fully aware of their long-term risk exposure and whether their risk perception changes over time. We leave these topics for future research.

6. Conclusion

This research presents one of the first attempts to empirically examine the current state of practices in adapting to extreme weather events within U.S. public transit agencies. Based on analysis of survey data collected from transit professionals who work in planning, operation, maintenance, and engineering, we show that transit agencies across the US have experienced extreme weather though the impact of extreme weather events varies depending upon event type, location, and transit mode.

It is evident that the realities of climate change are increasingly relevant for transit policy, planning and management. Increased frequency and severity of extreme weather events and the resulting impact on public transit agencies set the stage for a more visible national discussion to address climate impacts for transit. Concrete mechanisms at all levels of government must be devised that can better research, inform and support agencies as they make the short- and long-term decisions necessary to reduce vulnerability to extreme weather. On the research front, it is evident from this study that the economic impacts of extreme weather on an often severely aging infrastructure are not fully understood or acknowledged. It is likely that transit-dependent riders, especially those from lower income populations in urban areas, realize more significant downstream effects of climate change and extreme weather. While transit agencies need to move from a reliance on traditional emergency response approaches to being more proactive in the adaptive strategies, it is also true that federal and state grant systems need to better recognize and reward climate adaptation planning and management. Similarly, the private sector and professional associations should work in partnership with government on a solutions-oriented approach that more effectively and proactively addresses climate change challenges for transit and transportation in general.

The complex issues related to climate and extreme weather are not going to abate. Rather, they are likely to become more severe and more destructive. This study provides a preview of things to come as well as some insights into the agency-level constraints that must be traversed and opportunities to be leveraged. Ongoing work should continue to monitor, assess, report on and advocate for innovative programs and approaches to address climate change impacts on public transit.

Acknowledgment

This study was funded by the Federal Transit Administration, US Department of Transportation through the Metropolitan Transportation Support Initiative at UIC for 2015–2016.

Appendix A. . Summary statistics of responding transit agencies & individual respondents

Responding Agencies	N	%
Transit Mode		
Bus	188	94%
Heavy Rail	15	8%
Light Rail	40	20%
Water	9	5%
Region		
Pacific (CA, OR, WA)	48	24%
South Atlantic (DC, FL, GA, MD, NC, SC, VA, WV)	42	21%
New England (CT, MA, RI)	8	4%
Middle Atlantic (DE, NJ, NY, PA)	22	11%
Mountain (AZ, CO, NM, NV, UT)	11	6%
East South Central (AL, KY, TN)	9	5%

East North Central (IL, IN, MI, OH, WI)	36	18%
West South Central (AR, LA, TX)	14	7%
West North Central (KS, MO, NE)	9	5%

Respondent Characteristics	N	%
Gender		
Female	57	0.19
Male	249	0.81
Position		
Executive Leadership (CEO/GM)	52	18.31
Engineers	15	5.28
Maintenance	46	16.2
Operation	80	28.17
Planning	69	24.3
Safety	17	5.99
Other positions	5	1.76
Race		
White	233	0.80
Asian	9	0.03
African American	36	0.12
Native American	1	0.00
Other Races	11	0.03
Education		
Less than high school	1	0.34
High school	17	5.76
Some college	56	18.98
Bachelor	102	34.58
Master degree	106	35.93
Doctoral degree	0	0.00
Other graduate degrees	13	4.41

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.trd.2018.06.005.

References

Adger, W. Neil, Brown, K., Nelson, D.R., Berkes, F., Eakin, H., Folke, C., Galvin, K., Gunderson, L., Goulden, M., O'Brien, K., Ruitenbeerk, J., Tompkins, E., 2011. Resilience implications of policy responses to climate change. WIREs Clim. Change 2 (5), 757–766. http://dx.doi.org/10.1002/wcc.133.

Arana, P., Cabezudo, S., Peñalba, M., 2014. Influence of weather conditions on transit ridership: a statistical study using data from Smartcards. Transp. Res. A: Policy Pract. 59, 1–12.

Bedsworth, L.W., 2008. Climate change and California's local public health agencies. Public Policy Institute of California Working Paper.

Berkhout, F., 2012. Adaptation to climate change by organizations. WIREs: Clim. Change 3, 91–106.

Berrang-Ford, L., Ford, J.D., Paterson, J., 2011. Are we adapting to climate change? Global Environ. Change 21 (1), 25–33.

Changnon, S.A., 1996. Effects of summer precipitation on urban transportation. Clim. Change 32 (4), 481–494.

Chapman, L., 2007. Transport and climate change: a review. J. Transp. Geogr. 15, 354–367.

Chung, J., 2013. Severe weather advisory in effect for NYC. Gothamist, New York.

Cravo, V.S., Cohen, J.E., 2009. The impact of weather on transit revenue in New York City. In: Proceedings of the 88th Annual Meeting of the Transportation Research Board, Transportation Research Board of National Academies. Washington, DC.

DOT, 2014. Ensuring Transportation Infrastructure and System Resilience. U.S. Department of Transportation Climate Adaptation Plan, Washington, D.C.

Eiser, J.R., Bostrom, A., Burton, I., Johnston, D.M., McClure, J., Paton, D., van der Pligt, J., White, M.P., 2012. Risk interpretation and action: a conceptual framework for responses to natural hazards. Int. J. Disaster Risk Reduct. 1 (October), 5–16. http://dx.doi.org/10.1016/j.ijdrr.2012.05.002.

Flegenheimer, M., 2013. M.T.A. Chief announces storm plan for subways, buses and commuter trains. The New York Times. < http://cityroom.blogs.nytimes.com/2012/10/27/m-t-achief-announces-storm-plan-for-subways-buses-and-commuter-trains/?_r=0 > .

Folke, C., 2006. Resilience: the emergence of a perspective for social–ecological systems analyses. Global Environ. Change 16 (3), 253–267.

Friedman, D., 2014. MTA to receive $886M to fix subway tunnel damage caused by Hurricane Sandy. New York Daily News, retrieved from < http://www.nydailynews.com/new-york/mta-receive-886m-fix-damage-caused-hurricane-sandy-article-1.1587376 > .

Grothmann, T., Patt, A., 2005. Adaptive capacity and human cognition: the process of individual adaptation to climate change. Global Environ. Change 15 (3),

199–213.
Guo, Z., Wilson, N.H.M., Rahbee, A., 2007. Impact of weather on transit ridership in Chicago, Illinois. Transp. Res. Rec.: J. Transp. Res. Board 2034, 3–10.
Hegerl, G.C., Zwiers, F.W., Braconnot, P., Gillett, N.P., Luo, Y., Marengo Orsini, J.A., Nicholls, N., Penner, J.E., Stott, P.A., 2007. Understanding and Attributing Climate Change. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 663–745.
Hodges, T., 2011. Flooded bus barns and buckled rails: public transportation and climate change adaptation. Federal Transit Administration Report No. 0001. < https://trid.trb.org/view.aspx?id=1133763 > .
IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (eds.). A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA.
Koch, J., MacArthur, J.H., 2013. Assessing public transportation agencies' climate change adaptation activities and needs. In: Transportation Research Board 92nd Annual Meeting. < https://trid.trb.org/view.aspx?id=1242652 > .
Jochem, P., Rothergatter, W., Schade, W., 2016. Climate change and transport. Transp. Res. Part D: Transp. Environ. 45, 1–3.
Kalstein, A.J., Kuby, M., Gerrity, D., Clancy, J.J., 2009. An analysis of air mass effects on rail ridership in three U.S. cities. J. Transp. Geogr. 17 (3), 198–207.
Koetse, M.J., Rietveld, P., 2009. The impact of climate change and weather on transport: an overview of empirical findings. Transp. Res. Part D: Transp. Environ. 14 (3), 205–221. http://dx.doi.org/10.1016/j.trd.2008.12.004.
Linnenluecke, M.K., Griffiths, A., Winn, M., 2012. Extreme weather events and the critical importance of anticipatory adaptation and organizational resilience in responding to impacts. Bus. Strategy Environ. 21 (1), 17–32.
Nelson, D.R., Adger, W.N., Brown, K., 2007. Adaptation to environmental change: contributions of a resilience framework". Annu. Rev. Environ. Resour. 32 (1), 395–419. http://dx.doi.org/10.1146/annurev.energy.32.051807.090348.
NOAA, 2017. Billion-Dollar Weather and Climate Disasters (2017). < https://www.ncdc.noaa.gov/billions/ > .
Pregnolato, M., Ford, A., Wilkinson, S.M., Dawson, R.J., 2017. The impact of flooding on road transport: a depth-disruption function. Transp. Res. Part D: Transp. Environ. 55, 67–81.
Singhal, A., Kamga, C., Yazici, A., 2014. Impact of weather on urban transit ridership. Transp. Res. Part A 69, 379–391.
Smithers, J., Smit, B., 1997. Human adaptation to climatic variability and change. Global Environ. Change 7 (2), 129–146. http://dx.doi.org/10.1016/S0959-3780(97)00003-4.
Stamos, I., Mitsakis, E., Salanova, J.M., Aifadopoulou, G., 2015. Impact assessment of extreme weather events on transport networks: a data-driven approach. Transp. Res. Part D: Transp. Environ. 34, 168–178.
Stover, V.W., McCormack, E.D., 2012. The impact of weather on bus ridership in pierce county, Washington. J. Public Transp. 15 (1), 95–110.
Suarez, P., Anderson, W., Mahal, V., Lakshmanan, 2005. Impacts of flooding and climate change on urban transportation: a systemwide performance assessment of the Boston Metro Area. Transp. Res. D: Transp. Environ. 10, 231–244.
Thomson, B., 2017. Managing Extreme Weather at Bus Stops. Transportation Research Board, Washington, D.C.
Transportation Research Board, 2008. Potential Impacts of Climate Change on U.S. Transportation. TRB Special Report. < http://onlinepubs.trb.org/onlinepubs/trnews/trnews256climate.pdf > .
Tribbia, J., Moser, S.C., 2008. More than information: what coastal managers need to plan for climate change. Environ. Sci. Policy 315–328.
Xia, Y., Ommeren, Van, Jos, N., Rietveld, P., Verhagen, W., 2013. Railway infrastructure disturbances and train operation performance: The role of weather. Transp. Res. Part D: Transp. Environ. 18, 97–102.
Winn, M., Kirchgeorg, M., Griffiths, A., Linnenluecke, M.K., Günther, E., 2011. Impacts from climate change on organizations: a conceptual foundation. Bus. Strategy Environ. 20, 157–173.
Zhang, F., Welch, E.W., Miao, Q., 2018. Public organization adaptation to extreme events: mediating role of risk perception. J. Publ. Admin. Res. Theory. http://dx.doi.org/10.1093/jopart/muy004.